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A fast and high accurate initial values obtainment method for Brillouin scattering spectrum parameter estimation

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ABSTRACT

To improve accuracy and arithmetic efficiency of the parameter estimation for Brillouin scattering signal, on the basis of systematic analysis of the Lorentzian function, a fast and high accurate initial parameter estimation algorithm is proposed and it decreases the computational burden of the following least-squares fit. A three-parameter least-squares fit with a Levenberg–Marquardt optimization scheme is implemented in Matlab for the Brillouin scattering parameter estimation, and the random variable, the results from the particle swarm optimization (PSO) algorithm and the proposed algorithm are taken as the initial values of the above least-squares fit. Two numerically generated signals with considerable noise and one real signal are selected. The results reveal that the least-squares fit based on the random variable method almost never converges. However, both the PSO method and the proposed method can converge in various situations. The computation time of the PSO method ranges from 500 ms to 700 ms and that of the proposed method ranges from 1 ms to 3 ms, that is, the proposed method can guarantee convergence and at the same time, the arithmetic efficiency is greatly improved. The proposed method fixes the problem of fast and high accurate parameter estimation for Brillouin scattering.

1. Introduction

In the past decade, distributed fiber sensing especially those based on Brillouin scattering is attracting considerable research interest due to its unrivaled capability to provide a measured property of interest, such as strain or temperature, as a continuous function of linear position along the sensing fiber. The Brillouin scattering based technology has many advantages, including high spatial resolution, high accuracy and wide measurement range (longer than 100 km), etc. [1]. Therefore, it is extensively used in the power and oil industries and also in structural monitoring [2–4]. However, the Brillouin frequency shift and the power are the key for the simultaneous optical fiber distributed strain and temperature measurements [5]. For the Brillouin spectral profile, the total power is proportion to the peak value multiplied by the linewidth. As such, it is essential to obtain the Brillouin scattering's peak value, line width and central frequency, which are generally obtained by fitting [6,7]. In principle, due to the exponential decay of acoustic waves in fiber core, generally, the Brillouin gain has a Lorentzian spectral profile. Thereby, the parameter estimation of Brillouin scattering is realized by the least-squares Lorentzian fit [6,8] and some accurate parameter values can be obtained. However, the initial guesses have an important effect on the computation time and convergence of the least-squares fit and the bad initial values will decrease the arithmetic efficiency of the following least-squares fit, even lead to divergence and then the optimal Brillouin scattering parameters cannot be obtained. The particle swarm optimization (PSO) algorithm can be used to obtain the initial values [9] and the method is a global-optimal one. Therefore, the convergence of the following least-squares algorithm is significantly improved. However, the method still has the deficiency of large computational burden. As a result, it is difficult to estimate the Brillouin scattering parameters fast. However, the long distance fiber distributed Brillouin sensing system needs to process a large amount of data. Therefore, the real time is required for the parameters estimation [10] and this problem needs to be studied further.

To resolve the problem, the Lorentzian function is thoroughly investigated in the paper and the fast estimation method for the peak value of the gain, the line width and the central frequency is given. At the same time, the estimated parameter values are comparatively accurate. Thereafter, on the basis of these values, the Levenberg–Marquardt [11] based on least-squares fit is used to improve the accuracy of these parameters. Two numerically generated signals with considerable noise and one real

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signal are selected. The random variable method, the PSO algorithm, the proposed algorithm and the least-squares fit with a Levenberg–Marquardt optimization scheme are implemented in Matlab. The results validate the proposed method.

2. Principle of the proposed algorithm

When a small fraction of the incident light is inelastically scattered by thermally excited acoustic waves (acoustic phonons) in the optical fiber, spontaneous Brillouin scattering will take place. A periodic modulation of the dielectric constant and hence refractive index of the medium is generated due to density variations produced by the acoustic wave. The scattered light undergoes a Doppler frequency shift and has the maximum scattering in the backwards direction. And the above Doppler frequency shift is known as Brillouin frequency shift [7]. The strong attenuation of sound waves in silica determines the shape of the Brillouin gain spectrum. When the injection pulse width is much larger than 10 ns, the exponential decay of the acoustic wave results in a gain $g_B(\nu)$ presenting a Lorenzian spectral profile [12,13]:

$$g_B(\nu) = g_0 \frac{(\Delta\nu_B/2)^2}{(\nu-\nu_B)^2 + (\Delta\nu_B/2)^2} \tag{1}$$

where ν represents frequency (GHz); ν_B represents the Brillouin frequency shift (GHz), and it characterizes the difference between the central frequency of the Brillouin scattering spectrum and the frequency of the incident light. The Brillouin frequency shift of singlemode optical fiber is generally about 11 GHz, when the wavelength of incident light is 1550 nm. $\Delta\nu_B$ represents the full width at half maximum (FWHM) bandwidth of the Brillouin scattering spectrum and it is relevant to the lifetime of phonon; g_0 represents the peak value of the Brillouin gain spectrum.

To estimate $\Delta\nu_B$, ν_B and g_0, we can employ the gradient method [10] or the intelligence algorithm [7,9]. However, the initial values are the key factor influencing the convergence of the following least-squares fit. Therefore, based on the Lorentzian function, we make an effort to develop the fast estimation method for the peak value, line width and central frequency.

As can be seen from (1), if $\nu = \nu_B$, the Brillouin gain spectrum reaches its peak. Therefore, the estimated value of ν_B, that is, ν_{B0} is equal to the frequency corresponding to the maximum Brillouin gain spectrum. It is apparent that if $\nu = \nu_B$, then $g_B(\nu)$ equals to g_0. Therefore, the estimated value of g_0, that is, g_{00} is equal to the peak value of $g_B(\nu)$. If the frequency scan interval (frequency resolution) is high enough and the signal is noise-free, then the above estimation will work well. However, if the frequency scan interval is low and the signal has a bit high level of noise, the estimated values will introduce significant error and the estimation method needs to be improved further. After rearranging of (1), it can be written as follows:

$$\frac{1}{g_B(\nu)} = \frac{(\nu-\nu_B)^2 + (\Delta\nu_B/2)^2}{(\Delta\nu_B/2)^2 g_0} \tag{2}$$

From (2), the reciprocal of the Brillouin gain $1/g_B(\nu)$ is a 2nd degree polynomial of frequency ν. For low frequency scan interval or a high level of noise, the left and right N points around the peak value are selected and N can be set to 4 or some larger values according to the practical situations. The least-squares optimization procedure can be used to find the best fit of the 2nd degree polynomial to the relationship between $1/g_B(\nu)$ and ν. If the minimum value of the obtained second order polynomial is equal to P_m, then g_{00} is calculated by

$$g_{00} = \frac{1}{P_m} \tag{3}$$

If the frequency ν corresponding to the minimum value equals to ν_m, then ν_{B0} is given by

$$\nu_{B0} = \nu_m \tag{4}$$

On the basis of the above approach, the error of ν_B and g_0 caused by the low frequency scan interval or a high level of noise can be decreased and at the same time, the high arithmetic efficiency remains unchanged.

If $\nu = \nu_B$, the value of the Brillouin gain equals g_0. If $\nu = \nu_B + \Delta\nu_B/2$ or $\nu = \nu_B - \Delta\nu_B/2$, the value of the Brillouin gain equals $g_0/2$. Therefore, assume the left and right frequencies corresponding to $g_0/2$ are ν_{B2} and ν_{B3} respectively, then the estimated value of $\Delta\nu_B$, that is,

$$\Delta\nu_{B0} = |\nu_{B2} - \nu_{B3}| \tag{5}$$

Because the estimated values, ν_{B0}, g_{00} and $\Delta\nu_{B0}$ still have errors, the least-squares Lorentzian fit is used to further improve the accuracy of the above three parameters. Assume that ν_i is the ith scanned frequency value, $i = 1, 2, 3, \ldots, N$, and g_{Bi} is the ith sampled Brillouin gain, $i = 1, 2, 3, \ldots, N$. The least-squares problem is defined as

$$E = \frac{1}{2}\sum_{i=1}^{N} e_i^2 = \frac{1}{2}\sum_{i=1}^{N} (g_B(\nu_i) - g_{Bi})^2 \tag{6}$$

It is a nonlinear least-squares problem and the Levenberg–Marquardt algorithm is particularly suited to resolve the problem, especially for good initial values. $J_{i,j} = \partial e_i/\partial w_j$ is an element of the Jacobian matrix J, which is represented as

$$J_{i1} = \frac{\partial e_i}{\partial g_0} = \frac{(\Delta\nu_B/2)^2}{(\nu_i-\nu_B)^2 + (\Delta\nu_B/2)^2} \tag{7}$$

$$J_{i2} = \frac{\partial e_i}{\partial \nu_B} = \frac{2g_0(\Delta\nu_B/2)^2(\nu_i-\nu_B)}{((\nu_i-\nu_B)^2 + (\Delta\nu_B/2)^2)^2} \tag{8}$$

$$J_{i3} = \frac{\partial e_i}{\partial \Delta\nu_B} = g_0 \frac{\Delta\nu_B/2}{(\nu_i-\nu_B)^2 + (\Delta\nu_B/2)^2} - g_0 \frac{(\Delta\nu_B/2)^3}{((\nu_i-\nu_B)^2 + (\Delta\nu_B/2)^2)^2} \tag{9}$$

Suppose $\boldsymbol{e} = [e_1, e_2, \ldots, e_N]^T$ is the error vector, and $\boldsymbol{W} = [g_0, \nu_B, \Delta\nu_B]^T = [w_1, w_2, w_3]^T$ is the variable vector. $\boldsymbol{I}$ is a 3×3 unit matrix. Thus the variable update formula can be expressed as

$$\boldsymbol{W}(k+1) = \boldsymbol{W}(k) - (\boldsymbol{J}(k)^T \boldsymbol{J}(k) + \lambda \boldsymbol{I})^{-1} \boldsymbol{J}(k)^T \boldsymbol{e}(k) \tag{10}$$

where k is the number of iterations and $\boldsymbol{W}(k) = [g_{0k}, \nu_{Bk}, \Delta\nu_{Bk}]^T$. The initial value for damping parameter λ (λ_0) is assigned as 0.001. The parameter λ is multiplied by 10 whenever a step would result in an increased E. When a step reduces E, λ is divided by 10 [11]. When a step increases E, the adjustment of variables will be disregard and the last values of variables will be kept. A large amount of computation reveals that this setting will result in good results. The flow chart of the proposed algorithm is illustrated in Fig. 1.

We must take some random values within a certain range as the initial guess. On the basis of the practical situation, g_0 ranges form 0 to 1. Based on the fact that different fibers are of different Brillouin frequency shifts and at the same time, it will be influenced by temperature and strain. Therefore, ν_B ranges form 10 GHz to 13 GHz. For the ordinary singlemode fiber, $\Delta\nu_B$ mainly ranges from 0.03 GHz to 0.05 GHz. However in view of widening and compression of the spectrum, $\Delta\nu_B$ ranges form 0.01 GHz to 0.15 GHz. The PSO algorithm and the random variable method obtain their initial guesses according to these ranges.

PSO algorithm is implemented and the initial population number is 200. After a larger number of trials, the most suitable convergence criterion is determined and it can be expressed as